

Effects of Varying the Output of a Mechanical Left Ventricle on the Circulation in the Dog¹

EDWARD D. FREIS, HERBERT P. BROIDA, CHARLES A. HUFNAGEL AND
JOHN C. ROSE

From the Cardiovascular Research Laboratory, Georgetown University Hospital, the Departments of Medicine and Surgery, Georgetown University School of Medicine, and the Heat and Power Division, National Bureau of Standards, Washington, D. C.

THE EFFECTS of varying filling pressures and peripheral resistances upon the output of the isolated heart have been known since the Starling 'heart-lung preparation' was devised (1). In such experiments an intact heart and lung were used, the venous return and peripheral resistance being varied under controlled conditions. The reverse experiment, that of using an intact peripheral circulation and an artificial left ventricular pump, which can be varied at will over a wide range of outputs and rates, has not been attempted until recently. An experimental heart pump permitting such studies has been developed (2), and the present report is concerned with the effects of variations in rate and output of this pump upon systemic arterial, venous, and pulmonary arterial pressures and pulmonary blood flow.

MATERIALS AND METHODS

All experiments were carried out on healthy mongrel dogs weighing 16-25 kg. Each animal was anesthetized with sodium pentobarbital 25 mg/kg administered intravenously and maintained with endotracheal oxygen. A detailed description of the apparatus, the surgical technique for replacing the left ventricle with the artificial pump, and the methods of recording have been provided in a previous communication (2).

A pump output of 2000-2500 ml/min. was used at the time that the extracorporeal circulation was substituted. The systemic arterial pressure pulses were then observed for the presence of 'impure' pulse waves indicating a continued output from the left ventricle as well as from the pump (2). If such 'contaminated' waves were observed the drainage tube in the left auricle was adjusted until the pressure pulses became pure indicating that the bypass had become complete. In many instances contamination of the systemic arterial pulse waves with left ventricular blood could not be

completely eliminated, especially at high outputs. However, these were easily recognized by simple inspection of the tracings and were eliminated from the reported data. Although substitution of a pump for the left ventricle was carried out in 36 dogs (21 with the pump described) a major portion of the data reported here was obtained in five animals where complete satisfactory experiments were obtained.

RESULTS

Effects of Variations in Stroke Volume and Pump Rate With Constant Minute Outputs. If the minute output was constant proportionate variations in stroke volume and heart rate did not alter the mean arterial pressure. As the rate was decreased and the stroke volume increased proportionately to keep the minute output constant, there was an increase in pulse pressure due to both a rise in systolic pressure and a decrease in diastolic pressure (fig. 1). However, mean systemic arterial pressure, venous and pulmonary arterial pressures and return flow remained unchanged.

Right Ventricular Rate. Since only the left ventricle was being bypassed in these experiments right ventricular function remained intact. There was no tendency for the right ventricle to assume the same rate as the pump. There also were no consistent changes in right ventricular rate when the output of the left ventricular pump was changed. Marked increases in the left ventricular output from 1000 to more than 3000 ml/min. were not accompanied by an increase in the rate of the right ventricle. Thus, the changes in right ventricular output described below are due almost entirely to changes in stroke volume, rather than rate.

The mean right ventricular rate for the entire group of animals was 136 (range 75-180) beats/min. However, in the great majority of

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experiments the rates of the right ventricle varied between 120 and 160 beats/min. In any given animal the extreme range of change in rates during the experiment averaged 25 (range 10-45) beats/min. The changes observed, as stated above, however, followed no consistent pattern in relation to changes in pump output (table 1).

That this pattern of right ventricular response was not due to the presence of moderator reflexes is suggested by the fact that blocking doses of hexamethonium failed to alter the relative constancy of right ventricular rate. However, the right ventricle remained capable of increasing its rate during these experiments since if epinephrine was injected a significant tachycardia resulted.

Mean Arterial Pressure. At the lowest output of 1 l/min. the mean arterial pressure ranged between 58 and 64 mm Hg. As the outputs were increased there was a rise in arterial pressure. At the highest output of 3.5 l/min. the range of mean arterial pressure varied between 100 and 123 mm Hg. For a given change in output the increments in pressure usually appeared to be greater in the lower ranges of outputs than in the higher ranges. As the outputs were decreased the descending limb of the pressure output curve tended to approximate a mirror image of the ascending limb (fig. 2).

Pulmonary Arterial Pressure. The pressure in the pulmonary artery also rose with increases in output. The ranges of mean pulmonary arterial pressures were 11-20 mm Hg at outputs of 1.0 l/min. and 24-36 mm Hg at outputs

TABLE 1. RELATIONSHIP OF THE RATE OF THE INTACT RIGHT VENTRICLE TO STEPWISE ALTERATIONS IN MINUTE 'LEFT PUMP' OUTPUT

Pump Output, cc/min.	Right Ventricular Rate, strokes/min.				
	Dog 20	Dog 21	Dog 26	Dog 35	Dog 36
1000				150	
1250		140			
1500	150		144		90
1750	150	140		150	
2000				160	90
2250	150				
2500	150			160	90
3000			132	150	84
3250				150	
3500					90
3000			132		
2250	150				
2000	150				110
1750	150				
1500	150				
1250		120			
1000					120
Av. R.V. rate	150	140	140	155	90
Range R.V. rates	150	120-140	132-144	150-160	84-120

'Left pump' rate 100 strokes/min. in all experiments.

of 2.5 l/min. In the two animals in which the outputs were increased to 3.5 l/min. the pulmonary arterial pressures in both cases rose to 31 mm Hg.

When pressure changes were plotted against output changes on a semi-logarithmic scale there was a striking parallelism of pulmonary and systemic arterial pressure curves in the individual dog (fig. 2). In all five dogs the slope and configuration of the pulmonary arterial pressure curve closely patterned the systemic arterial curve for each animal. In addition, the position of the pulmonary and systemic pressure-output curves for each dog in relation to the curves for the other dogs was the same in both the pulmonary and systemic graphs.

Since, as discussed below, there was storage of blood in the dogs' vascular system when the pump outputs were increased, it seemed possible that the parallelism between pulmonary and systemic pressure-output curves in individual dogs was due to proportionate increases in blood volume in the pulmonary and systemic arteries. If this were the case, however, the blood storage curve should parallel the pressure curves. Blood volume changes were deter-

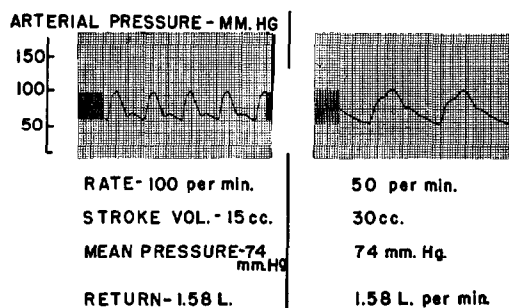


FIG. 1. Cuttings of systemic arterial pressure pulses in a pump dog showing that at a constant pump output of 1500 cc/min. alterations in rate alter only the pulse pressure. The mean arterial pressure and venous and pulmonary arterial pressures as well as total left auricular return flow remain the same.

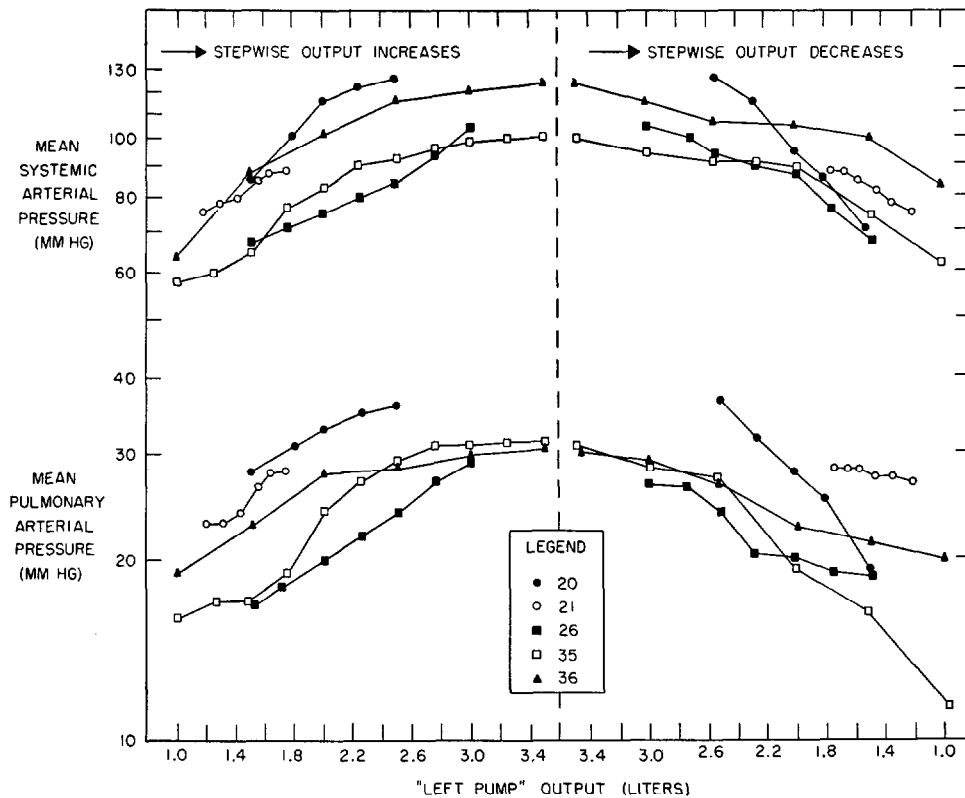


FIG. 2. Chart showing the logarithmic plot in 5 dogs, systemic arterial pressure and mean pulmonary arterial pressure against pump output as the outputs are increased and then decreased in steps. See text for discussion.

mined in dogs 35 and 36. As the outputs were increased there was no close parallelism between the curves of blood storage and pressure (fig. 3).

Venous Pressure. The responses of venous pressure to changes in pump output were small (fig. 4). At the lowest pump outputs the venous pressures varied between 20 and 55 mm H₂O and at the highest outputs between 50 and 60 mm H₂O. It must be emphasized that when the heart begins to fail the venous pressures become much higher than those reported here (3).

Although the venous pressure did not parallel the systemic arterial pressure as closely in the individual dogs as did the pulmonary arterial pressure, the directional trends were the same. It should be pointed out that the venous pressure was difficult to measure accurately because of the small magnitude of the changes and also because of fluctuations produced by the positive pressure respirator.

Possibly under more ideal conditions a closer parallelism with arterial pressure might have been observed.

Pulmonary Blood Flow. When the pump outputs increased the animal took up blood from the reservoir and when they decreased the reverse occurred with bleeding of the animal into the reservoir. Thus, in six experiments (in 4 dogs) in which the pump output was increased by 1 liter usually in steps of 250 cc there was a loss from the reservoir varying between 250 and 475 cc (average 345 cc) (table 2). Similarly, in the same experiments, when the outputs were decreased to the original level there was a gain in reservoir volume varying between 50-500 cc (average 300 cc). The greatest change in reservoir level occurred usually within the first 10 seconds after the pump output had been altered. After 30 seconds the reservoir level became constant indicating that the pulmonary blood flow was now equal to the output of the pump. At a later

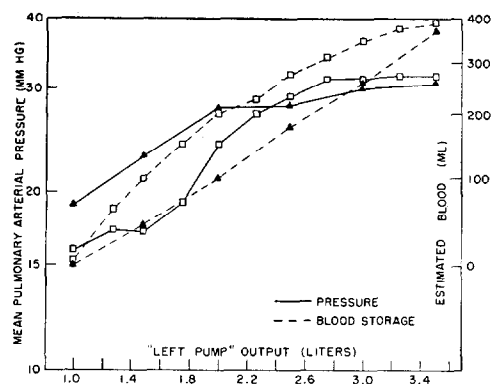


FIG. 3. Chart constructed to compare alterations in mean pulmonary arterial pressure and blood storage in 2 dogs as pump outputs are increased in steps. The MPA pressures are plotted logarithmically. Blood storage is plotted on a similar scale for purposes of comparison. See text for discussion.

stage in each experiment one of the indications of the onset of circulatory failure was a failing reservoir level even when the output was maintained at a constant value.

DISCUSSION

Mean arterial pressure was uninfluenced by changes in rate and stroke volume so long as the minute output was kept constant. This effect has been surmised by others (4) but the evidence has not been conclusive due to the fact that in the intact animal changes in rate or stroke volume probably result in changes in minute output. Thus, Wiggers describes experi-

ments in which cutting the vagi to produce tachycardia or infusing blood or saline to increase stroke volume resulted in an increase in mean arterial pressure (4). As a corollary, vagal stimulation or hemorrhage reduced mean pressure. In all of these experiments it was recognized that the minute output changed. In the present experiments rate and stroke volume could be varied without changing minute output. By this means it has been demonstrated conclusively that mean pressures and flows in the circulation are dependent upon minute output and not upon stroke volume or heart rate, per se.

When the stroke volume was increased and the rate proportionately decreased with constant minute output there was a slight increase in systolic and decrease in diastolic pressure. These changes can be explained readily by the well known fact that the pressure pulse varies with cardiac ejection and arterial drainage (5). When cardiac ejection increases systolic pressure rises and when cardiac rate decreases arterial drainage is more complete resulting in a reduction of diastolic pressure.

Despite marked increases in pump output with which the intact right ventricle kept pace there were no significant changes in right ventricular rate. It is obvious, therefore, that the increase in right ventricular output was accomplished entirely by an increase in right ventricular stroke volume rather than by rate changes. Thus, in agreement with Ballin and

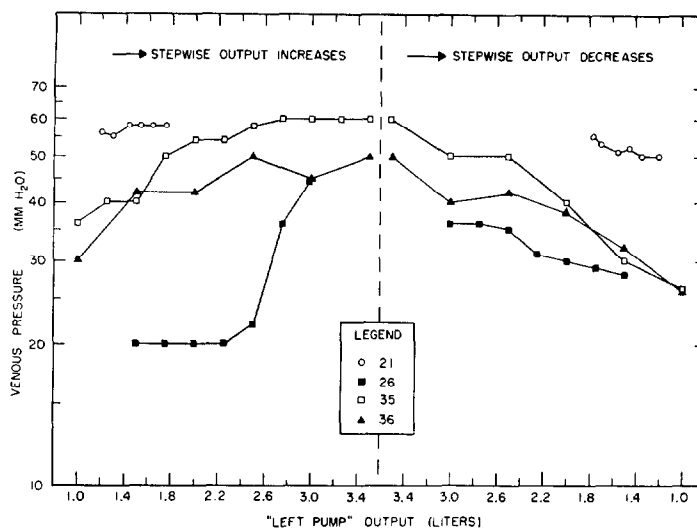


FIG. 4. Chart showing the logarithmic plot, in 4 dogs, of pressure against minute pump output as the outputs are increased and then decreased in steps. See text for discussion.

Katz (6), there was no evidence for the operation of a Bainbridge type of reflex in these experiments. These results are also similar to those obtained by Patterson, Piper and Starling in the isolated heart lung (7). There was a crude, non-linear relationship between changes in right ventricular stroke volume and venous pressure.

In contrast to the absence of change in mean arterial pressure with proportionate changes in rate and stroke volume there was a significant increase in mean pressure when the minute output was elevated. The fact that the increments in pressure usually were less at higher outputs indicated that the peripheral resistance decreased as the outputs were increased. The shape of the pressure output curve cannot be explained by variations in blood storage since the curve of blood storage during increasing outputs failed to parallel the pressure curve (fig. 3). The reason for the observed pressure output curve, therefore, is not apparent at this time and requires further study.

Equally difficult to explain is the unusual parallelism observed between the pulmonary and systemic pressure output curves. The most striking observation was that the shape and position in relation to the other animals of the pulmonary pressure-output curve for each dog was generally the same as the shape and position of the systemic pressure-output curve for that dog. Again the shape of these curves did not correlate with the blood storage curve. This observation suggests the possibility of an integrative mechanism whereby vasomotor tone is regulated simultaneously in the pulmonary and systemic circulations. However, no such integrative mechanism has been demonstrated or even suggested previously.

As the pump outputs were increased there was a brief period in which the pump output exceeded the pulmonary venous drainage into the reservoir. It is primarily during this period that blood is stored. After this initial adjustment period the pulmonary venous drainage approaches the pump output and eventually an equilibrium is reached. The equilibrium is associated with an increase in intravascular pressures and a decrease in reservoir level as compared to the equilibrium existing prior to the increase of output. The rise in all of the pressures suggests that the excess blood is

TABLE 2. GAINS AND LOSSES IN BLOOD VOLUME WITH 1000 CC/MIN. INCREMENTS AND DECREMENTS IN 'LEFT PUMP' OUTPUT

<i>Increasing Output</i>		
Dog No.	Output Alteration, cc/min	Blood Vol. Gain, cc
31	1000-2000	475
34	1050-2100	325
35	1000-2000	400
	2000-3000	300
36	1000-2000	250
	2000-3000	325
Av.		345
<i>Decreasing Outputs</i>		
Dog No.	Output Alteration, cc/min	Blood Vol. Loss, cc
31	2000-1000	450
34	2100-1050	400
35	3000-2000	225
	2000-1000	500
36	3000-2000	50
	2000-1000	150
Av.		300

stored in both the greater and lesser circulations. That the storage is not primarily in the large veins is suggested by the fact that, when the right ventricle is functioning effectively as in these experiments, the venous pressure may not show much change. This is in contrast to the dog with a poorly functioning right ventricle, however, who as will be shown in a later communication, exhibits marked elevations of venous pressure (3). An exactly opposite sequence of events occurs when the pump output is decreased.

SUMMARY AND CONCLUSIONS

A diaphragm type pump with independent controls of rate and stroke volume was substituted for the left ventricle in dogs and the following observations made: mean arterial pressure was a function of minute output rather than of stroke volume or ventricular rate, per se. Increase in stroke volume with maintenance of a constant minute output by proportional reduction of pump rate produced an increase of pulse pressure without change in mean pressure. Increase in pump output produced parallel increases in the output of the intact right ventricle. The increase in right ventricular output was accomplished almost entirely by an increase in stroke volume rather than in right

ventricular rate. With stepwise increases and then decreases in pump output the mean systemic and pulmonary arterial pressures usually exhibited parabolic pressure output curves characterized generally by larger pressure increments and decrements at the lower outputs. The pulmonary pressure output curve tended to parallel the systemic curve in individual dogs. The reasons for these characteristics of the pressure-output curves are not clear at this time. Increase in pump output in these experiments produced blood storage. When the right ventricle was functioning efficiently there were negligible changes in venous pressure, suggesting that the excess blood was not stored primarily in the large veins.

This technique appears to provide a method

for exploring the responses of the cardiovascular system to controlled changes in left ventricular output.

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